may include spiral conductive patterns having alternating orientations according to substrate layer.

[0072] The implementation of inductor 500 shown in FIGs. 7A and 7B provides another illustration of this alternating orientation feature. In this implementation, spiral conductive patterns 510, 708, and 512 are disposed on adjacent surfaces 530, 730, and, 532, respectively. As shown in FIG. 7A, spiral conductive pattern 510 has a clockwise orientation, and spiral conductive pattern 708 has a counterclockwise orientation. Furthermore, in this implementation, spiral conductive pattern 512 has a clockwise orientation.

[0073] A further example of this alternating orientation feature is described with reference to the implementation shown in FIG. 8. In this implementation, spiral conductive patterns 510, 804, 808, 812, and 512 are disposed on adjacent surfaces 530, 830, 832, 834, and 532, respectively. In this implementation, these conductive patterns may have orientations based on the layer-based alternating orientation scheme described above. For example, patterns 510, 808, and 512 may each have a clockwise orientation, while patterns 804 and 812 each have a counterclockwise orientation. Similarly, the implementation of FIG. 8 may alternatively employ the opposite orientation relationship.

[0074] As described above, multiple layer inductor 500 may include an optional bottom shield pattern 516 and/or an optional top shield pattern 518. To further reduce unwanted electromagnetic interaction between inductor 500 and other electronic components (not shown), inductor 500 may also include side shield patterns disposed on each surface that includes a spiral conductive pattern. FIGs. 11 and 14 provide views of exemplary side shields.

[0075] FIG. 13 is a top view of a side shield 1302 disposed on a surface having a spiral conductive pattern 1304, a first terminal 1306a and a second terminal 1306b. Side shield 1302 does not completely surround pattern 1304 and terminals 1306. Instead, side shield 1302 provides an opening 1310 that enables the coupling of traces (not shown) to terminals 1306.

[0076] Spiral pattern 1304 and terminals 1306 are similar to spiral conductive pattern 510, terminal 504, and terminal 506, as described herein with reference to FIGs. 5-6. Accordingly, implementations of inductor 500 may include a side shield, such as side shield 1302, to surround spiral conductive pattern 510 in the manner shown in FIG. 13. Such side shields may have a voltage potential, such as ground.

[0077] FIG. 14 is a top view of a side shield 1402 disposed on a surface that also has a spiral conductive pattern 1404, but no terminals. Side shield 1402 completely surrounds conductive pattern 1404. One or more of the spiral conductive patterns of multiple layer inductor 500 may be surrounded by a side shield, such as side shield 1402, having a voltage potential, such as ground.

III. Inductor Design Procedure

[0078] The inductance of multiple layer inductor 500 can be mathematically estimated through Equation (1), below.

$$L = \frac{37.5\mu_o n^2 a^2}{22r - 14a} \qquad (1)$$

[0079] In Equation (1), L represents the inductance of multiple layer inductor 500 in Henries, μ_o represents the permeability of free space, n represents the total number of turns in all of the spiral conductive patterns of inductor 500, r represents the outer radius for each of the spiral conductive patterns in meters, and a represents the mean radius for each of the spiral conductive patterns in meters. Further explanation Equation (1) is provided in H. A. Wheeler, "Simple Inductance Formulas for Radio Coils," *IRE Proceedings*, 1928, pg. 1398, as quoted in T. H. Lee, The Design of CMOS Radio Frequency Integrated Circuits, Cambridge University Press, 1998, pp. 48-49. These documents are incorporated herein by reference in their entirety.

[0080] The present invention includes a procedure of designing multiple layer inductor 500. This procedure involves the use of Equation (1) to generate inductor characteristics according to a target inductance. FIG. 15 is a flowchart illustrating an operational sequence of this procedure. This sequence begins with a step 1502. In step 1502, a number of spiral conductive patterns is determined for inductor 500. This number may be as large as the number of substrate layers. However, when bottom and/or top shields are desired, this number will be one or two layers less to accommodate the bottom and/or top shields.

[0081] Next, in a step 1504, a spiral shape is selected. As described above with reference to FIGs. 9-10, exemplary shapes include round spiral shapes, square spiral shapes, rectangular spiral shapes, hexagonal spiral shapes, and octagonal spiral shapes. However, other shapes may be selected.

[0082] A step 1506 follows step 1504. In this step, the spatial characteristics of each of the spiral conductive patterns is defined. These spatial characteristics include line width, w, outer radius, r, inner radius i, and mean radius, a, as expressed above in Equation (1). The range of available line widths and spiral sizes is determined by various factors, such as the process employed to manufacture the substrate (e.g., the PCB).

[0083] Next, a step 1508 verifies the performance of a multiple layer spiral inductor having the determined number of spiral conductive patterns, the selected spiral shape, and the defined spatial characteristics. FIG. 15 shows that step 1508 includes steps 1510 through 1520.

[0084] In step 1510, an inductance is calculated an inductance based on the determined number of spiral conductive patterns, the selected spiral shape, and the defined spatial characteristics. This calculation may be performed according to Equation (1). In step 1512, it is determined whether the calculated inductance is substantially equal to a target inductance. If so, then the procedure continues to step 1514. Otherwise, the procedure returns to step 1502, so that steps 1502 through 1506 may be repeated.